Tillage Effects on Physical Properties in Two Soils of the Northern Great Plains

J. D. Jabro, W. B. Stevens, R. G. Evans, W. M. Iversen

Abstract. *Tillage practices profoundly affect soil physical and hydraulic properties. It is essential to select a tillage practice that sustains the soil physical properties required for successful growth of agricultural crops. We evaluated the effects of conventional (CT) and strip (ST) tillage practices on bulk density (ρ_b), gravimetric water content (θ_w), and saturated hydraulic conductivity (K_s) at the soil surface and at 10- to 15-cm depth in two soils of the Northern Great Plains (NGP). Soil cores were collected from each plot at 0- to 10- and 10- to 20-cm depths under each tillage practice at both sites to measure ρ_b and θ_w.* In-situ *K_s measurements at the soil surface and at 10- to 15-cm depth were determined using a pressure head infiltrometer (PHI) and a constant head well permeameter (CHWP), respectively, at two sites, one in North Dakota (Nesson, mapped as Lihen sandy loam) and one in Montana (EARC, mapped as Savage clay loam). The K_s measurements were made approximately 1 m apart in the center of crop rows within CT and ST plots of irrigated sugarbeet (*Beta vulgaris *L.). Tillage treatments significantly affected soil ρ_b and θ_w in clay loam soil at the EARC site, while ρ_b and θ_w did not differ between CT and ST in sandy loam at the Nesson site. The log-transformed K_s at the soil surface did not differ significantly between CT and ST practices at either site. The effect of tillage on log-transformed K_s at the 10- to 15-cm depth was significant in both sandy loam and clay loam soils at $P < 0.10$ and 0.05 levels, respectively. The K_s values at 10- to 15-cm depth were 23% and 138% greater for ST than for CT at Nesson and EARC sites, respectively. Differences in soil compaction as evaluated through ρ_b data at 10- to 20-cm depth explain K_s variations between the CT and ST systems at both sites. It was concluded that the CT operations increased soil compaction, which consequently altered ρ_b, thereby reducing K_s in the soil.*

Keywords*. Bulk density, Infiltration, Hydraulic conductivity, Soil compaction.*

The rate at which water enters into the soil surface (infiltrability) and transmits through the soil profile (saturated hydraulic conductivity) depends on soil structure, pore size distribution, and pore continuity (Hillel, 1971; Klute, 1986; Reynolds and Elrick, 2002). These soil properties are all affected by tillage, one of the most influential management practices influencing soil physical and hydraulic characteristics (Lal and Shulka, 2004).

Tillage can alter soil structure by creating macropores that considerably increase saturated hydraulic conductivity (Bouma, 1991). The reverse effect is observed when wheel traffic induces soil compaction and subsequent destruction of soil macropres (Ankeny et al., 1990). Tillage can affect pore size distribution by creating temporary pore spaces that either collapse or seal during the growing season as a result of raindrop impact and wetting and drying cycles (Topaloglu, 1999). And tillage practices can disrupt pore continuity and macropores, reducing water flow between the plow layer and subsoil (Bouma, 1991).

Two of the most commonly measured soil physical properties affecting hydraulic conductivity and other hydraulic properties are the soil bulk density and effective porosity, as these two properties are also fundamental to soil compaction and related agricultural management issues (Strudley et al., 2008). Although *in-situ* saturated hydraulic conductivity (K_s) is considered one of the most important parameters for water flow and chemical transport phenomena in soils (Reynolds and Elrick, 2002), relatively few studies have evaluated and compared the effects of various tillage practices on physical and hydraulic properties of the soil.

Topaloglu (1999) found that tillage practices had no appreciable effect on infiltration rates in sandy clay loam soils. Ankeny et al. (1990) noted no differences in infiltration rates between tilled and untilled soils, while Heard et al. (1988) observed higher infiltration rates in tilled soils and attributed the difference to soil surface sealing in untilled soils. Allmaras et al. (1977) determined that soil hydraulic conductivity was greater in chisel-plowed plots than untilled soil due to greater soil aggregation resulting from the chiseling practice. Chan and Mead (1989) noticed that untilled soils exhibited greater hydraulic conductivities than tilled soils and attributed the difference to decreased soil bulk density and improved porosity where there was no tillage. It is clear that reports of tillage effects on soil structure, macropore modifications, and other physical properties at the field scale are often contradictory (Lal and Van Doren, 1990; Coutadeur et al., 2002).

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The ambiguous nature of these research findings demonstrates the need for additional studies of the effect of various tillage practices on soil physical characteristics. Moreover, little research has been reported regarding the effect of strip tillage on these soil properties. In light of this, we sought to evaluate the effects of conventional (CT) and strip (ST) tillage practices on bulk density (ρ_b), gravimetric water content (θ_w), and saturated hydraulic conductivity (K_s) at the soil surface and at 10- to 15-cm depth in two soils of the U.S. Northern Great Plains.

Materials and Methods

Study Site Description

The study sites were situated on two soil types differing in soil texture in two sprinkler-irrigated fields within a semi-arid region of the U.S. Northern Great Plains. Soil physical properties measurements were made at two sites, one in North Dakota (Nesson) and the other in Montana (EARC).

North Dakota (Nesson) Site Characteristics and Experimental Design

The North Dakota research site is located at the Nesson Valley MonDak Irrigation Research and Development Project (48.1640° N, 103.0986° W), approximately 37 km east of Williston, North Dakota. The soil is mapped as Lihen sandy loam (sandy, mixed, frigid Entic Haplustoll) consisting of very deep, somewhat excessively or well drained, nearly level soil that formed in sandy alluvium, glacio-fluvial, and eolian deposits in places over till or sedimentary bedrock (www.ftw.nrcs.usda.gov). The sandy Lihen soil series is a minor soil type in the Northern Great Plains (NGP) region but provides a contrasting soil type for comparison with the clay-textured Savage soil.

The experimental design at the Nesson site is a randomized complete block design with six replications. Treatments consist of two crop rotations [sugarbeet/ potato (*Solanum tuberosum* L.)/malting barley (*Hordeum vulgare* L.) and sugarbeet/malting barley/potato], two tillage practices (conventional and strip) under sugarbeet, and were irrigated as needed using a linear-move overhead sprinkler system to maintain 50% and 100% plant available water. This study utilized data from only the sugarbeet plots under both tillage systems. In June 2006, measurements of the various parameters were made within 1 m of each other at randomly selected locations in each plot so as to lie in the center of crop rows. Each measurement was replicated 12 times. Measurements were made when the initial water content in the soil was below the field capacity level of 0.23 m^3 m^{-3} (Jabro et al., 2009) (average initial water content was approximately 0.15 m^3 m^{-3}).

Montana (EARC) Site Characteristics and Experimental Design

The Montana research site is located at the Montana State University Eastern Agricultural Research Center (EARC) approximately 2 km north of Sidney, Montana (47.7255° N, 104.1514° W). The EARC soil is a deep, well drained, nearly level Savage clay loam (fine, smectitic, frigid Vertic Argiustolls) that formed in alluvium parent material (www.ftw.nrcs.usda.gov). The Savage soil series is similar to most of the irrigated soils in central and eastern Montana, which are located primarily in Yellowstone and Missouri river valleys.

The experimental design at the EARC site was an unbalanced block arrangement of two cropping systems, namely CT-sugarbeet/CT-malting barley and ST-sugarbeet/ CT-malting barley with each phase of each rotation present each year. Each rotation was replicated 14 times, but the unbalanced design resulted in each component crop's being replicated either six or eight times varying by year. Plots were irrigated using a linear-move overhead sprinkler system to maintain soil moisture above 50% plant-available water. In June 2006, measurements of the various parameters were made within 1 m of each other at randomly selected locations in each plot so as to lie in the center of crop rows. Each measurement was replicated 8 times. Measurements were made when the initial soil water content was below the field capacity level of 0.34 m^3 m^{-3} (Jabro et al., 2009) (average initial water content was approximately 0.226 m^3 m^{-3}).

Conventional Tillage (CT)

The barley crop at both sites was harvested in late summer 2005 and the resulting straw and chaff were uniformly spread on the plots by the combine harvester. The stubble height after harvest was approximately 18 cm. Following barley harvest, plots at the EARC site were fertilized and disked (9/12/2005) 10 to 12 cm deep with a tandem disk (John Deere 640, John Deere, Moline, Ill.), then ripped twice to a depth of 28 to 30 cm (9/13/2005) using a ripper (Case-IH 6810, Case-IH, Racine, Wis.) with a 60-cm shank spacing and equipped with high clearance vibra tines and a rolling leveler attachment. Sugarbeet was planted on 1 May 2006 using a John Deere 4455 tractor and John Deere 1700 MaxEmerge II Plus planter (John Deere, Moline, Ill.). The crop was cultivated on 8 and 22 June 2006 using the same tractor used for planting but equipped with a single-shank row crop cultivator (6R-24SB H&S cultivator, H&S, Stephen, Minn.).

The CT plots at the Nesson site were tilled just prior to planting in the spring of 2006, an intentional difference in farming practice to minimize overwinter wind erosion on this sandy soil. The plots were fertilized and disked 12 cm deep on 26 April 2006. The following day all plots were chisel-plowed with straight shovels to a depth of 28 cm. One pass was made with a cultipacker (seedbed preparation implement) immediately following the chisel plowing. Sugarbeet seeds were planted on 29 April 2006 with the same tractor and planter used at the EARC site. The crop was cultivated as described for the EARC site on 5 and 28 June 2006.

Strip Tillage (ST)

The barley crop was harvested as described for the CT treatment. The ST operation was completed at EARC on 13 September 2005 and at Nesson on 28 September 2005 using a six-row strip tiller set to a depth of 20 cm with a straight coulter in front of a semi-parabolic shank followed by two wavy coulters and a crowsfoot packer wheel (Schlagel TP 6524, Schlagel Mfg., and Torrington, Wy.) that tills 30-cm strips and leaves 30 cm of standing stubble between tilled rows. A tube mounted on the rear of the shank placed dry fertilizer 10 cm deep in the tilled zone. No additional field operations, other than spraying for weed and insect control, were performed until planting and cultivating, which took place on the same dates as for the CT plots.

Measurement of Bulk Density (ρ_b) and Gravimetric Water Content (θ_w)

Using a core sampler, undisturbed cylindrical soil samples (5 cm long × 5 cm in diameter) were collected from each plot at 0- to 10- and 10- to 20-cm depths under each tillage system at both sites. Soil cores were used to measure bulk density (ρ_b) as mass of oven-dried soil per volume of core (Mg m^{-3}) and gravimetric water content (θ_w) as mass of water in the soil sample per mass of the oven dried soil (kg kg^{-1}). Each measurement was replicated 8 and 12 times for the EARC and Nesson sites, respectively.

Field-Saturated Hydraulic Conductivity at the Soil Surface (K_s)

Soil K_s at the surface was determined at both sites using the single-head pressure ring infiltrometer method under steady-state conditions (Reynolds and Elrick, 2002). The pressure head ring infiltrometer (PHI) consists of a Mariotte-type reservoir, similar to that of the constant head well permeameter (CHWP), sealed to a stainless steel ring with a radius of 10 cm, driven to a depth of 5 cm into the soil surface (Reynolds and Elrick, 2002).

One-dimensional water flow in the infiltration ring, followed by divergent three-dimensional flow below the ring, was calculated using:

$$K_S = \frac{GQ}{G\,\pi\alpha^2 + a\,(H + \alpha^{-1})} \tag{1}$$

where K_s (L T^{-1}) is the field-saturated hydraulic conductivity at the soil surface, G is a dimensionless shape parameter determined by the numerical solution of Richard's equation (Reynolds and Elrick, 2002), given as:

$$G = 0.316\frac{d}{a} + 0.184 \tag{2}$$

d is the depth of ring insertion into the soil (L), a is a radius of the stainless steel ring (L), Q is a steady-state flow rate out of the PHI and into the soil (L^3 T^{-1}), H is the steady depth of water inside the ring (L), and α is a soil texture/structure parameter (L^{-1}) identical to that in the CHWP.

Field-Saturated Hydraulic Conductivity below the Soil Surface (K_s)

Steady-state water flow rates were measured at the Nesson and EARC sites using a CHWP (Reynolds et al., 1985). For each measurement, a 6-cm diameter cylindrical hole was augured to a depth of 10 to 15 cm. A rigorous brush was used to prepare a clean borehole to minimize wall smearing (Reynolds, 1993). One set of steady flow rate measurements was made at a constant pressure head of 5 cm water for each hole (Elrick et al., 1989; Salverda and Dane, 1993). Steady-state flow rates were assumed after three consecutive readings were approximately the same.

In-situ K_s (L T^{-1}) using a steady state flow rate of water from a cylindrical borehole, augured to a given depth below the soil surface, was calculated using Richards' analysis (Reynolds et al., 1985):

$$K_s = \frac{CQ}{\left[2\pi H^2 + C\pi r^2 + \left(\frac{2\pi H}{\alpha}\right)\right]} \tag{3}$$

where C is a dimensionless shape factor that depends primarily on the H/r ratio and soil texture/structure properties and is a function of both H and r (C = 0.803), Q is the steady-state flow rate out of the borehole (L^3 T^{-1}), H is the steady depth of water in the hole (L), r is the radius of the hole (L), and α is a soil texture/structure parameter (L^{-1}) set to α = 36 m^{-1} for sandy loam and α = 12 m^{-1} for clay loam soil (Elrick et al., 1989).

Further detail on the PHI and CHWP apparatuses, procedures, and calculations can be found in Reynolds (1993) and Reynolds and Elrick (2002).

Statistical Analysis

Statistical analysis of data was conducted using the Analysis of Variance (ANOVA) of repeated measures in the mixed model procedure of SAS software (Littell et al., 1996). Soil K_s values were checked for normality of distribution using SAS probit procedures (SAS Institute, 2003). The K_s measurements at both the soil surface and 10- to 15-cm depth were found to be well described by a log-normal distribution. The logarithmic-transformed K_s values for both the Nesson and EARC sites were analyzed using the ANOVA procedure for mixed models (Littell et al., 1996).

Results and Discussion

Soil particle size distribution of Nesson and EARC experimental sites are given in table 1. Soil texture for Nesson and EARC sites was confirmed to be sandy loam and clay loam, respectively. Soil ρ_b was used as an index to evaluate soil compaction under each tillage system. As soil ρ_b is the most commonly measured soil property affecting hydraulic processes (Strudley et al., 2008), we provide a brief discussion of ρ_b data as influenced by CT and ST systems in order to understand the effects of CT and ST practices on K_s.

Soil physical properties were measured at two different depths to determine if the effect of tillage was consistent throughout the tillage layer. There was no interaction between tillage and depth at either site for any of the soil parameters, indicating that the effect of tillage was uniform across both depths. Moreover, soil depth did not affect the soil parameters with the exception of ρ_b at EARC site, where ρ_b was 9% higher at the 10- to 20-cm depth than at the 0- to 10-cm depth. Because there was no tillage × depth

Table 1. Soil particle size distribution at the 0- to 10-cm and 10- to 15-cm depths for Nesson and EARC sites. [a]

Site	Depth (cm)	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Soil Textural Class
Nesson	0-10	660	170	170	Sandy loam
	10-15	670	160	170	Sandy loam
EARC	0-10	230	420	35	Clay loam
	10-15	240	420	34	Clay loam

[a] Each measurement was replicated six times.

interaction and only a small depth main effect, only the tillage main effects will be presented.

Tillage treatments significantly ($P < 0.05$) affected soil ρ_b and θ_w at the EARC site, while ρ_b and θ_w did not differ between CT and ST at the Nesson site (table 2). Generally, soil ρ_b was greater in CT plots than in ST plots at both sites, suggesting that the CT operations increased soil compaction due to frequent traffic passes induced by this tillage system. Nevertheless, ST is perceived as having greater porosity and wetter soil conditions compared with CT (Licht and Al-Kaisi, 2005). Our results support this premise by virtue of ρ_b values that are 7.5% lower with ST than with CT at the EARC site (table 2). A similar trend was observed at the Nesson site, but the means were not significantly different. Elimination of secondary tillage and more limited vehicular traffic in ST plots probably contributed to decreased ρ_b and increased porosity compared to CT plots as the ST system includes only a single in-row soil disturbance event that decreases soil ρ_b and conserves water more than the CT system (Licht and Al-Kaisi, 2005). Results showed that differences in ρ_b and θ_w between CT and ST were more evident in the clay loam soil (EARC) than in the sandy loam (Nesson). This may be the result of differences in moisture-holding capacity or susceptibility to compaction between the two soil types. Soil moisture content at the time traffic occurs (Sánchez-Girón et al., 2001) and soil texture (McBride, 1989) have been shown to be soil properties that have a major influence on susceptibility to compaction. Soils with high moisture content (Soane et al., 1980) and/or high clay content (McNabb and Boersma, (1996) have been described as being highly susceptible to compaction.

The log-transformed K_s at the soil surface and at 10- to 15-cm depth under both CT and ST tillage systems at Nesson and EARC sites are illustrated in figures 1 and 2, respectively. The data showed that K_s at the soil surface did not differ significantly between CT and ST practices at either site (fig. 1). The similarity in K_s between CT and ST at the surface suggests that the CT and ST tillage systems are similar in terms of soil disturbance at this depth.

The effects of tillage on log-transformed K_s at the 10- to 15-cm depth were significant in both sandy loam and clay loam soils at 0.10 and 0.05 probability levels, respectively

Table 2. Effect of tillage on soil bulk density (ρ_b) and gravimetric water content (θ_w) averaged across two depths (0-10 and 10-15 cm) for conventional (CT) and strip (ST) tillage practices at Nesson and EARC sites.

Site	Tillage	ρ_b (Mg m^{-3})	θ_w (m^3 m^{-3})
Nesson	CT	1.56^{a}[a]	0.116^{a}
	ST	1.51^{a}	0.121^{a}
		Analysis of Variance, P > F	
		0.294	0.637
EARC	CT	1.46^{a}	0.145^{a}
	ST	1.37^{b}	0.172^{b}
		Analysis of Variance, P > F	
		0.025	0.0006

[a] Means followed by the same letter are not different at the 0.05 probability level ($p < 0.05$).

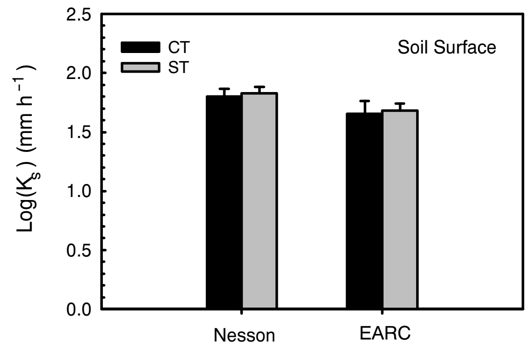

Figure 1. *In situ* saturated hydraulic conductivity (K_s) at the soil surface as affected by conventional tillage (CT) and strip tillage (ST) practices at the Nesson and EARC sites. Error bars are two standard errors of the mean. Tillage effects means are not significantly different.

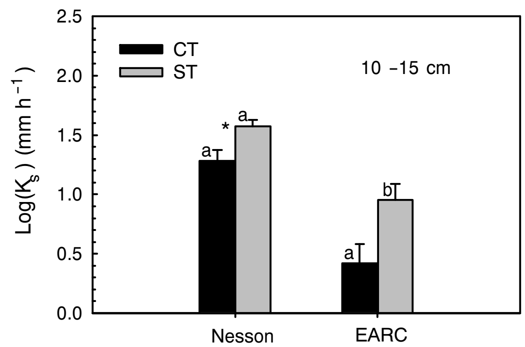

Figure 2. *In situ* saturated hydraulic conductivity (K_s) at 10- and 15-cm depth as affected by conventional tillage (CT) and strip tillage (ST) practices at the Nesson and EARC sites. Error bars are two standard errors of the mean. Different letters indicate that means are significantly different at the 0.05 probability level. An asterisk ('*') indicates that a difference is significant at the 0.10 probability level.

(figs. 1 and 2). The K_s values at the 10- to 15-cm depth were 23% and 138% greater for ST than for CT at Nesson and EARC sites, respectively.

Results in table 2 and figures 1 and 2 showed that K_s increases as the ρ_b decreases and soil voids increase, indicating that soil compaction influences K_s measurements at the 10- to 15-cm depth. These results suggest that the CT operations increased soil compaction, which consequently altered soil ρ_b and porosity, thereby reducing K_s (figs. 1 and 2). It is generally accepted that K_s is inversely related to ρ_b (Mankin et al., 1996). Our results agree with this premise in that higher ρ_b was associated with lower K_s values at the 10- to 15-cm depth at both the Nesson and EARC sites. Moreover, the ST system likely produced a greater volume of macropores (Wienhold and Tanaka, 2000; Lipiec et al., 2005), resulting in more pronounced vertical pore connectivity in ST plots than in CT plots. As a consequence, water flow through the soil profile was greater in ST plots than in CT plots where the macropores discontinued as soil depth increased due to soil compaction developed by this type of tillage.

The CT system consists of several more field passes (six passes) of equipment in which the wheel traffic is not confined to the inter-row area (between crop rows). The tires contact approximately 30% of the width tilled by implements; as multiple passes are required to prepare the seedbed, it is probable that most of the plot area was influenced by at least one tire track. In the ST system, the heavy wheel traffic was confined to the inter-row area where K_s measurements were not taken.

Effects of different tillage practices on soil physical properties and water movement through the soil may be useful to help explain some differences in sugarbeet crop growth and yield. Results of this study revealed that ST system increased K_s in the soil more than CT system at the 10- to 15-cm depth at both sites and this difference in K_s was more pronounced in clayey soil than in sandy soil. However, results are limited to the conditions of this study, namely fall tillage in small grains crop residues. It is conceivable that under different crop residue or climate conditions results may be different. For example, fall tillage in the Northern Great Plains subjects the tilled soil to freezing and thawing cycles that affect soil structure. Further research is necessary to determine whether similar effects would be observed when tillage is performed in the spring or in a climate where freezing temperatures do not occur.

Conclusions

Tillage treatments significantly affected soil ρ_b and θ_w in clay loam soil at the EARC site, while ρ_b and θ_w did not differ significantly between CT and ST in sandy loam at the Nesson site. Soil ρ_b was generally lower in ST plots than in CT plots while θ_w was greater for ST than for CT regardless of soil type.

The log transformed K_s at the soil surface did not differ significantly between CT and ST practices at either site. The effect of tillage on log-transformed K_s at the 10- to 15-cm depth was significant in both sandy loam and clay loam soils at $P < 0.10$ and 0.05 levels, respectively. The K_s values were always greater in ST plots than CT plots at both sites. The K_s values at the 10- to 15-cm depth were 23% and 138% greater for ST than for CT at Nesson and EARC sites, respectively.

The variation in K_s values in soil at 10- to 15-cm depth was likely due to differences in soil compaction and vehicular traffic passes peculiar to the CT and ST systems. The ST plots likely had better volume of macropores than CT plots, producing greater water flow through the ST soil profile and consequently enhanced water storage capability as reflected by wetter soil conditions under ST system.

The tillage practice selected -- whether CT, ST, or any alternative -- impacts soil physical properties and may affect crop growth and yield by enhancing water movement and retentivity, increasing soil aeration, and minimizing physical limitations that restrict root growth and distribution.

The conclusions drawn from this study can be generalized to soils similar to Lihen and Savage soil series as well as their soil associations.

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